

Constraints Imposed on LHC Commissioning Currents Due to Transverse Collective Modes and Chromaticity

J. Scott Berg*

Abstract

There are two situations during commissioning in which it is desired to have less current than the nominal total current, but in which the operating conditions may be less than optimal. This report examines what constraints will be imposed on these situations by the growth rates of transverse instabilities when compared to Landau damping thresholds. The first situation is when there is only a single “pilot” bunch in the machine at injection energy, with a current which is significantly less than the nominal single-bunch current, the initial goal being from 3 to 10% of the nominal single-bunch current. The purpose of such a running condition is to measure and correct the lattice parameters. Thus, in this situation, one expects to have a chromaticity which is not well-corrected, and no feedback system. The second situation is when there are the nominal number of bunches in the ring, but with less current than the nominal current, the initial goal being 16% of the nominal current. The chromaticity will be more well-controlled, but the feedback system may not be in operation. This report computes what the coherent frequencies of transverse modes would be in these situations for various chromaticities and currents, and indicates what constraints will be placed on the machine operation due to transverse instabilities.

*CERN–SL Division

Administrative Secretariat
LHC Division
CERN
CH-1211 Geneva 23
Switzerland

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1 Introduction

During commissioning of the LHC, one would like to be able to operate the machine under conditions which are less than ideal. One therefore needs to run at lower currents to compensate for this. Because of these less-than-ideal conditions, transverse collective effects may cause the beam to become unstable at significantly lower currents than it would under ideal conditions. This report computes what constraints will be placed on the beam current as well as other conditions so that the beam will remain stable against transverse collective instabilities.

The first situation considered is that of a single “pilot” bunch which will be used to determine and correct the lattice parameters of the machine at injection energies. Ideally, this pilot bunch should have from 3 to 10% of the nominal bunch current [Col97]. At this stage, the chromaticity will not be known or controlled very well (for example, due to uncorrected snap-back of the persistent currents in the dipoles), and the feedback system will not be in operation. Section 2 gives the results of a computation of the transverse modes for several currents up to 10% of the nominal bunch current, and for chromaticities $\xi = \Delta Q/(\delta p/p)$ as negative as -150 . It then describes which of these situations are stable due to Landau damping.

The second situation considered is when the machine is being run with all 2835 bunches, but at less than the nominal current, the initial goal being 16% of the nominal current [The95]. At this stage, there may not be feedback to correct the growth rates of the $m = 0$ multibunch modes. The chromaticity is expected to be controlled at least to within 15 units (a larger chromaticity would give a tune footprint which overlaps significant resonances). Section 3 gives the results of a computation of the transverse modes for currents up to 16% of the nominal current, and for chromaticities as negative as -15 . It then describes which of these situations are stable due to Landau damping. Note that if the current is 16% of nominal, the transverse normalized emittance is expected to be $1 \mu\text{m-rad}$, as opposed to $3.75 \mu\text{m-rad}$ at the nominal current [Col97].

In performing the computation, the impedance model and parameters described in [Ber96b] are used. An updated version of the program described in [Ber96a] is used to compute the mode frequencies. Several approximations are made for the system:

- The bunches are assumed to have a longitudinally Gaussian distribution for the purpose of computing the mode frequencies. This assumption does not apply to the computation of Landau damping thresholds.
- For the multibunch case, the ring is assumed to be symmetrically filled with 3564 bunches. “Nominal current” for these computations gives all bunches the nominal single-bunch current; thus, the total current is higher than the nominal total current. In most cases this probably gives more correct results than making the total currents agree.

1.1 Landau Damping

The threshold for Landau damping is computed using the methods described in [BR96]. The same method can in general be applied to a transverse parabolic-like distribution which goes to zero at $y = \sqrt{2\mu}\sigma_y$ for a general μ [Ber] (the quasi-parabolic distribution in [BR96] corresponds to $\mu = 5$). At injection from the SPS, the distribution will be collimated at 3 to 4σ [Col97], whereas in the LHC itself it will be collimated at 6σ [The95]. For stability, one must be under the stability curves corresponding to *both* of these distributions, plus the distributions in-between (i.e., corresponding to all cutoffs in the range of 3 to 6σ). Assuming that the betatron tune shift from zero amplitude for

a particle whose maximum amplitude is 10σ is limited to 5×10^{-3} by dynamic aperture constraints, and that the tune shift is linear in the action, the tune shift from nominal at $J = \epsilon$, where ϵ is the transverse emittance, is limited to 10^{-4} . Given that there will be 9 octupoles per arc per family as specified in [GKR97], the maximum tune shift at $J = \epsilon$ that can be achieved at top energy for the nominal emittance ($3.75 \mu\text{m-rad}$ normalized) is 1.2×10^{-4} . Thus, this paper assumes that the octupole strength is set to achieve a tune shift of 10^{-4} (except in one case).

The octupoles will be placed near the quadrupoles in the arcs. The arc quadrupoles are such that:

- All focusing quadrupoles have the same beta-functions, and all defocusing quadrupoles have the same beta-functions.
- β_y for a defocusing quadrupole is the same as β_x for a focusing quadrupole, and vice-versa.

Assuming that the octupoles are distributed such that there are the same number near the focusing quadrupoles as near the defocusing quadrupoles, and that the beam is round ($\epsilon_x = \epsilon_y$), the behavior for Landau damping purposes (i.e., the Landau damping curves) will be the same for whichever plane of oscillation one is referring to. Also, the ratio of the tune shift with amplitude in the plane of motion to the tune shift with amplitude perpendicular to the plane of motion is fixed and is determined by the beta-functions at the quadrupoles. Hence, if

$$\nu_x(J_x, J_y) = \nu_{x0} + a_{xx} \frac{J_x}{\epsilon_x} + a_{xy} \frac{J_y}{\epsilon_y} \quad (1)$$

$$\nu_y(J_x, J_y) = \nu_{y0} + a_{yx} \frac{J_x}{\epsilon_x} + a_{yy} \frac{J_y}{\epsilon_y}, \quad (2)$$

then $a_{xx} = a_{yy}$, $a_{yx} = a_{xy}$, and

$$\frac{a_{yy}}{a_{yx}} = -\frac{4\beta_D\beta_F}{\beta_D^2 + \beta_F^2}, \quad (3)$$

where β_D and β_F are the beta-functions at the defocusing and focusing quadrupoles respectively. For the LHC, these values are $\beta_D = 32.5 \text{ m}$ and $\beta_F = 175.5 \text{ m}$ [GKR97]. Thus, this paper assumes (with one exception) that $a_{xx} = a_{yy} = \mp 10^{-4}$ and $a_{xy} = a_{yx} = \pm 0.72 \times 10^{-4}$. Note that a_{xx} and a_{xy} have opposite signs; the paper will refer to the sign of a_{xx} to indicate which case is being considered.

2 Single Bunch

Figure 1 shows the coherent complex frequencies for a pilot bunch for various values of the chromaticity and bunch current. It demonstrates that for a_{xx} positive, one can run with currents as high as 10% of the nominal single-bunch current and chromaticities as large as -150 . With a_{xx} negative, one is limited to a chromaticity of -78 , or one can reduce the current to 8% of nominal to be able to have chromaticity as large as -150 . Higher order modes do not give stronger limitations.

3 Multiple Bunches

At injection energy, Fig. 2 demonstrates that at 10% of the nominal current, one can run with chromaticities as negative as -15 , assuming that a_{xx} is negative. There are a couple of modes which are unstable at the largest chromaticities, but these correspond to the 516.7 MHz and 1117.9 MHz higher-order modes in the feedback cavities, which can in

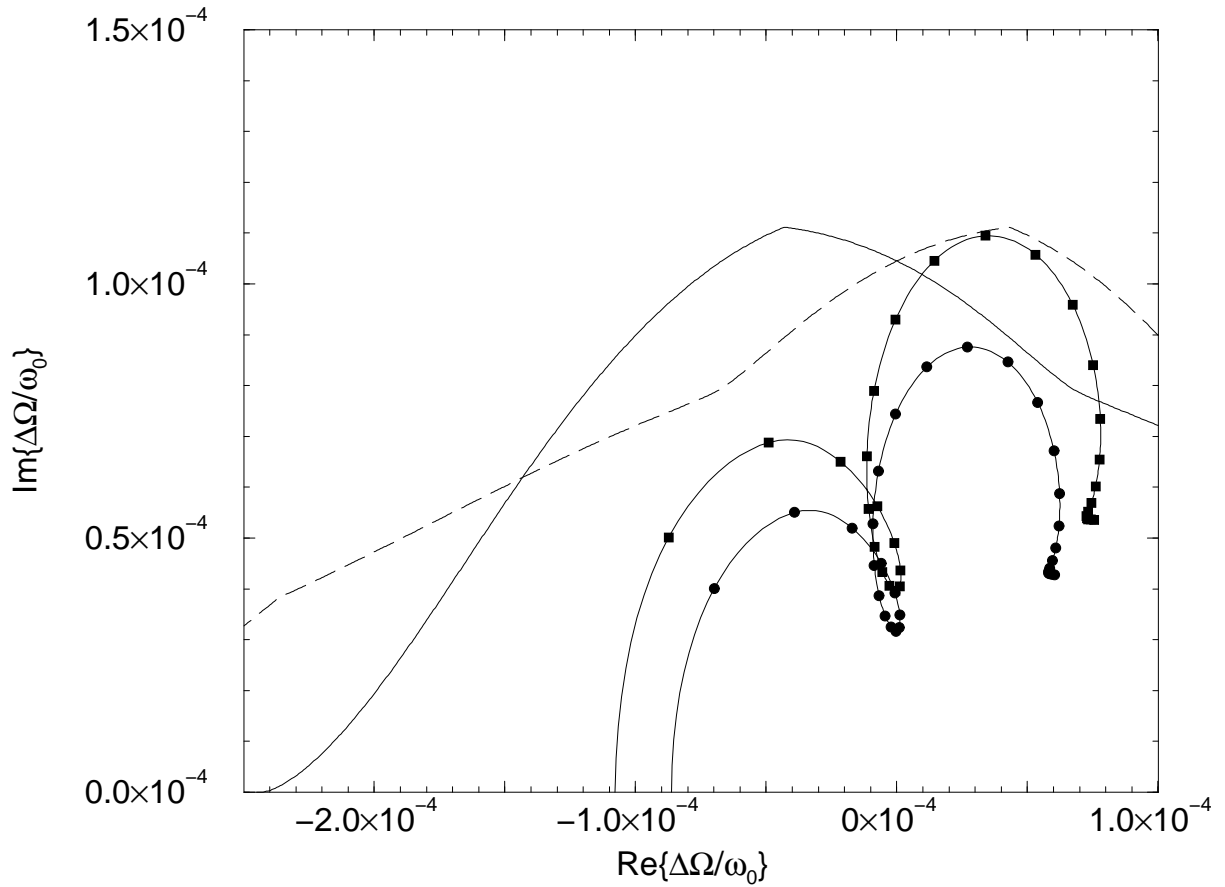


Figure 1: Complex coherent frequencies of the $m = 0$ mode for a pilot bunch at injection for various currents and chromaticities, compared to Landau damping threshold curves. The \bullet correspond to a bunch at 8% of the nominal single bunch current, and the \blacksquare to 10% of the nominal single bunch current. The separation between two consecutive symbols corresponds to a chromaticity change of 5 units. The curves are plotted for a chromaticity ranging from 0 to -150 . The curves without symbols are Landau damping threshold curves. The solid line is for a parabolic-like distribution which goes to zero in the range of 3σ – 6σ for a_{xx} negative (see the introduction), and the dashed line is the same but with a_{xx} positive. Note that for positive chromaticity, all the $m = 0$ modes are stable.

principle be damped somewhat [Höf96]. Thus, these modes shouldn't cause difficulties at the currents under consideration. If the a_{xx} is positive, the current will be limited to 8% of the nominal current if one wants to have chromaticities as large as -15 , the limiting instability in this case being due to the resistive wall impedance. When the current gets larger, there is a more significant limitation on the chromaticity as demonstrated in Fig. 3. One must run at chromaticities more positive than those given in the following table:

Current	$a_{xx} > 0$	$a_{xx} < 0$
11%	-1	-1
12%	1	0
14%	2	1
16%	3	2

In all these cases, the resistive wall instability is the limiting factor.

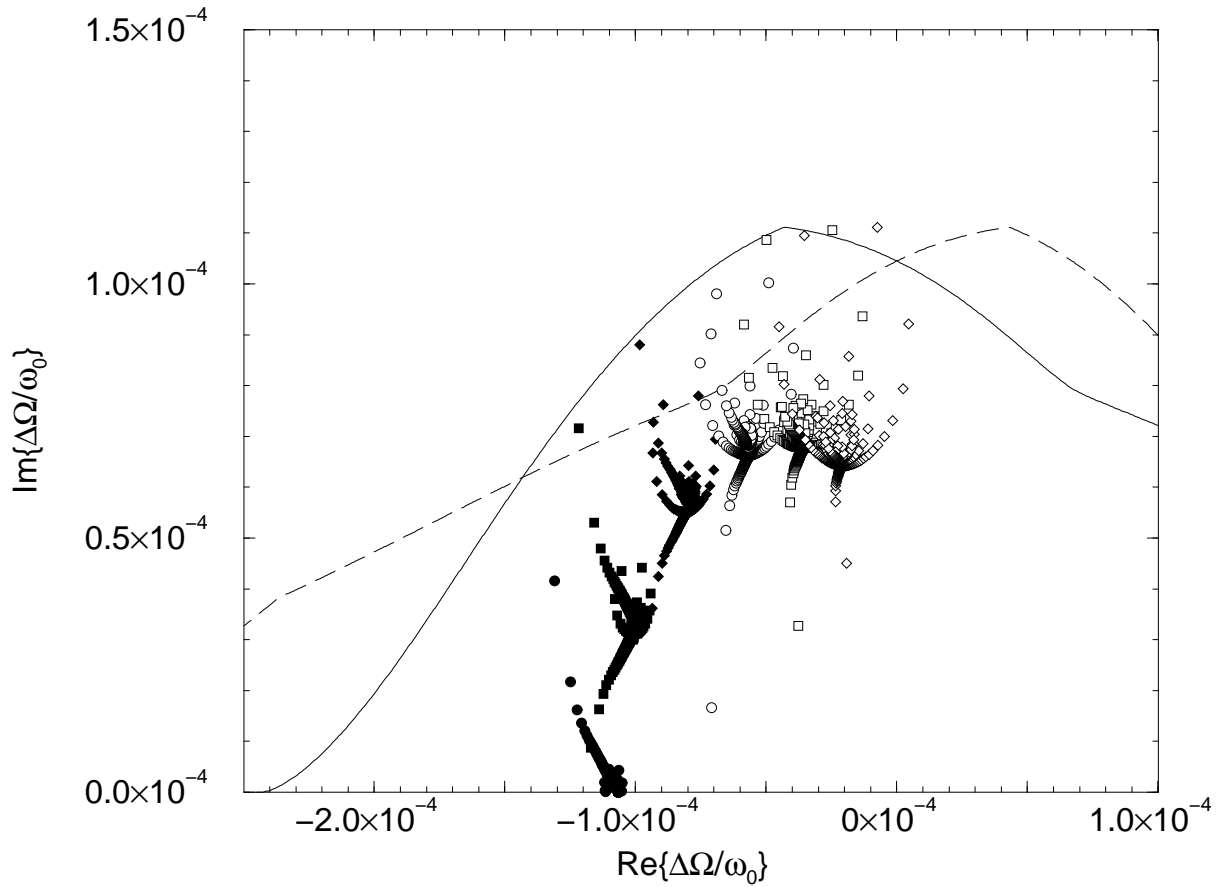


Figure 2: Complex coherent frequencies of all $m = 0$ modes for multiple symmetric bunches at injection with 10% of the nominal current, compared to Landau damping threshold curves. The \bullet are for a chromaticity ξ of 0, the \blacksquare for $\xi = -3$, the \blacklozenge for $\xi = -6$, the \circ for $\xi = -9$, the \square for $\xi = -12$, and the \diamond for $\xi = -15$. The curves without symbols are the same Landau damping threshold curves as in Fig. 1. Positive chromaticities are significantly more stable.

For positive chromaticity, higher order modes can potentially limit the operating current more than $m = 0$ modes. However, this is not a problem for the currents in question, as demonstrated in Fig. 4. There is also a potential effect on the Landau damping of higher order modes due to tune spread induced by space charge and longitudinal tune shift with amplitude, neither of which has been considered here.

At top energy (7 TeV), the situation changes significantly:

- The space charge part of the impedance nearly goes away.
- The bunch gets shorter.
- The energy is higher.
- The emittance decreases.
- The bunch has filled out transversely to 6σ .

The net result of these effects is that the coherent frequency shifts are reduced significantly from the case at injection. If one assumes that the octupole strengths are maintained such that the shift in ν_y at $J_x = 0$ and $J_y = \epsilon$ is $\pm 10^{-4}$, one is well inside the Landau damping threshold curves for chromaticities as large as -15 .

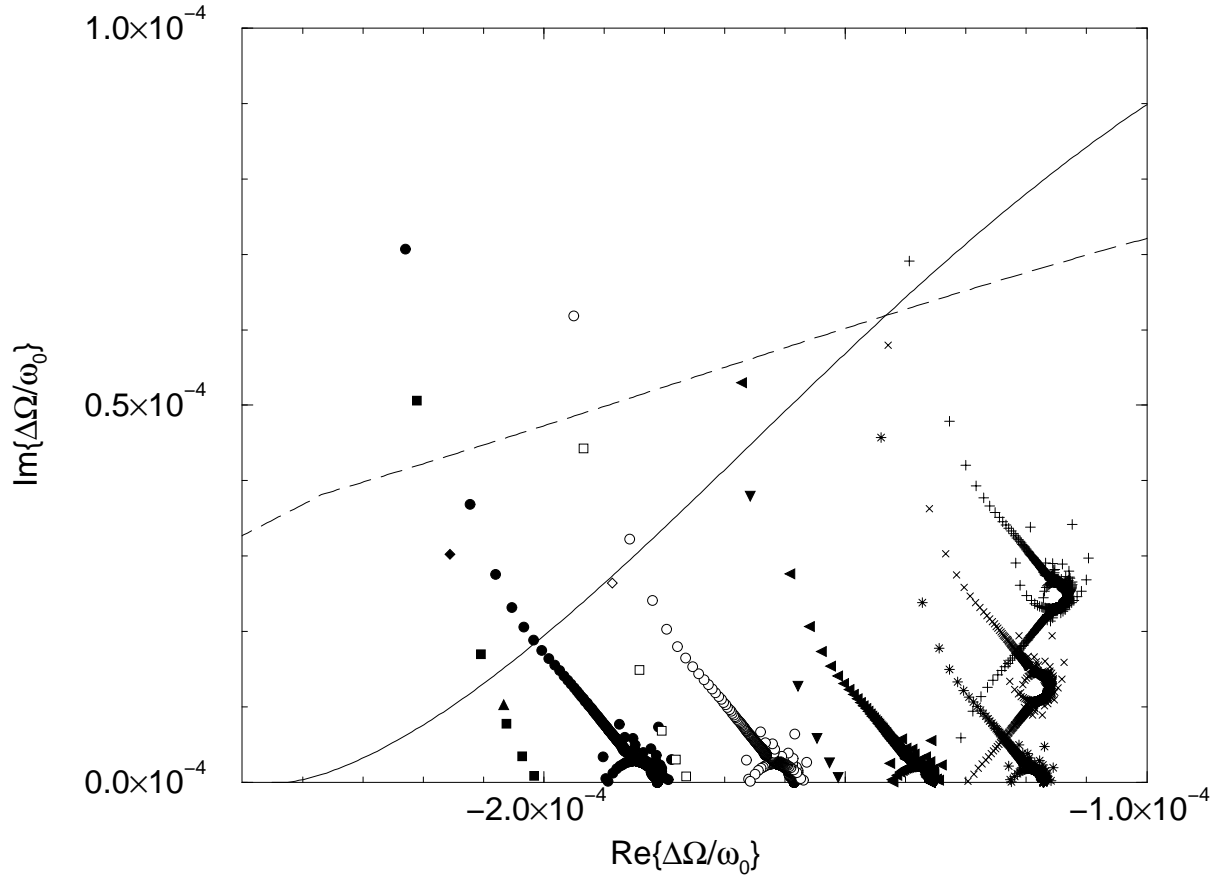


Figure 3: Complex coherent frequencies of $m = 0$ modes for multiple symmetric bunches at injection with currents larger than those in Fig. 2, compared to Landau damping threshold curves. The various symbols correspond to currents I and chromaticities ξ as follows:

Symbol	I	ξ	Symbol	I	ξ	Symbol	I	ξ	Symbol	I	ξ
•	16%	0	▲	16%	3	◊	14%	2	+	11%	-2
■	16%	1	○	14%	0	◄	12%	0	×	11%	-1
◆	16%	2	□	14%	1	▼	12%	1	*	11%	0

The curves without symbols are the same Landau damping threshold curves as in Fig. 1. Note that the range of $\Delta\Omega$ shown here is smaller than in previous figures. Positive chromaticities are more stable.

However, because of the reduced emittance, $a_{xx} = a_{yy}$ is limited to $\mp 3.2 \times 10^{-5}$, and $a_{xy} = a_{yx}$ is limited to $\pm 2.3 \times 10^{-5}$, for the strength of the octupoles as described in the introduction. This significantly reduces the Landau damping that one can obtain. However, Fig. 5 demonstrates that even with 16% of the nominal current, one is still safely within Landau damping thresholds. Higher order modes do not give stronger limitations.

4 Conclusions

A pilot bunch run in the LHC without feedback and with poorly-controlled chromaticity is stable against the head-tail instability for currents as high as 10% of the nominal current.

For multiple bunches without feedback, transverse instabilities will not prevent the machine from running with chromaticities as large as -15 and the current below about

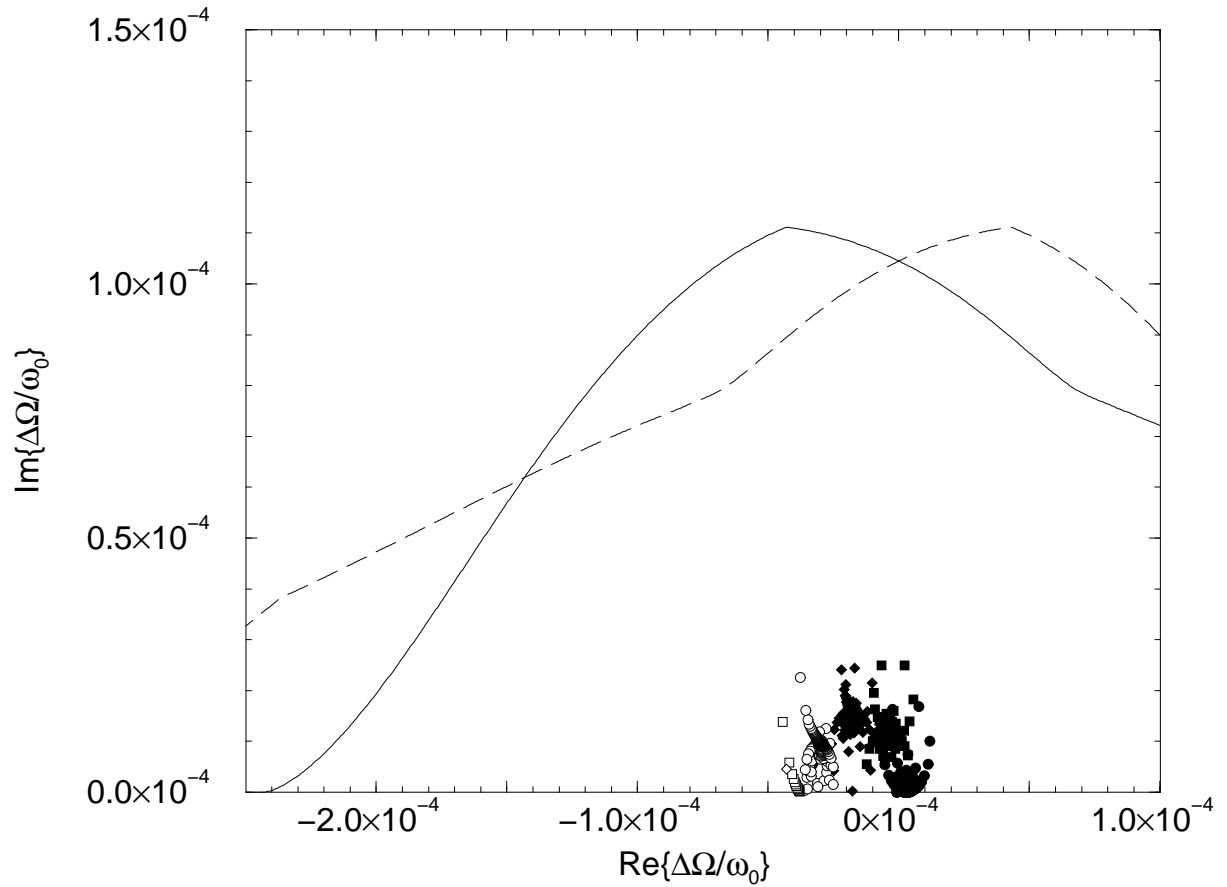


Figure 4: Complex coherent frequencies of $m = 1$ modes for multiple symmetric bunches at injection with 16% of the nominal current, compared to Landau damping threshold curves. The \bullet are for a chromaticity ξ of 0, the \blacksquare for $\xi = 3$, the \blacklozenge for $\xi = 6$, the \circ for $\xi = 9$, the \square for $\xi = 12$, and the \diamond for $\xi = 15$. The curves without symbols are the same Landau damping threshold curves as in Fig. 1.

10% of the nominal current. To run at currents much larger than this, the chromaticity must be maintained slightly positive. Transverse modes are stable for 16% of the nominal bunch current as long as the chromaticity is maintained at +2 or above.

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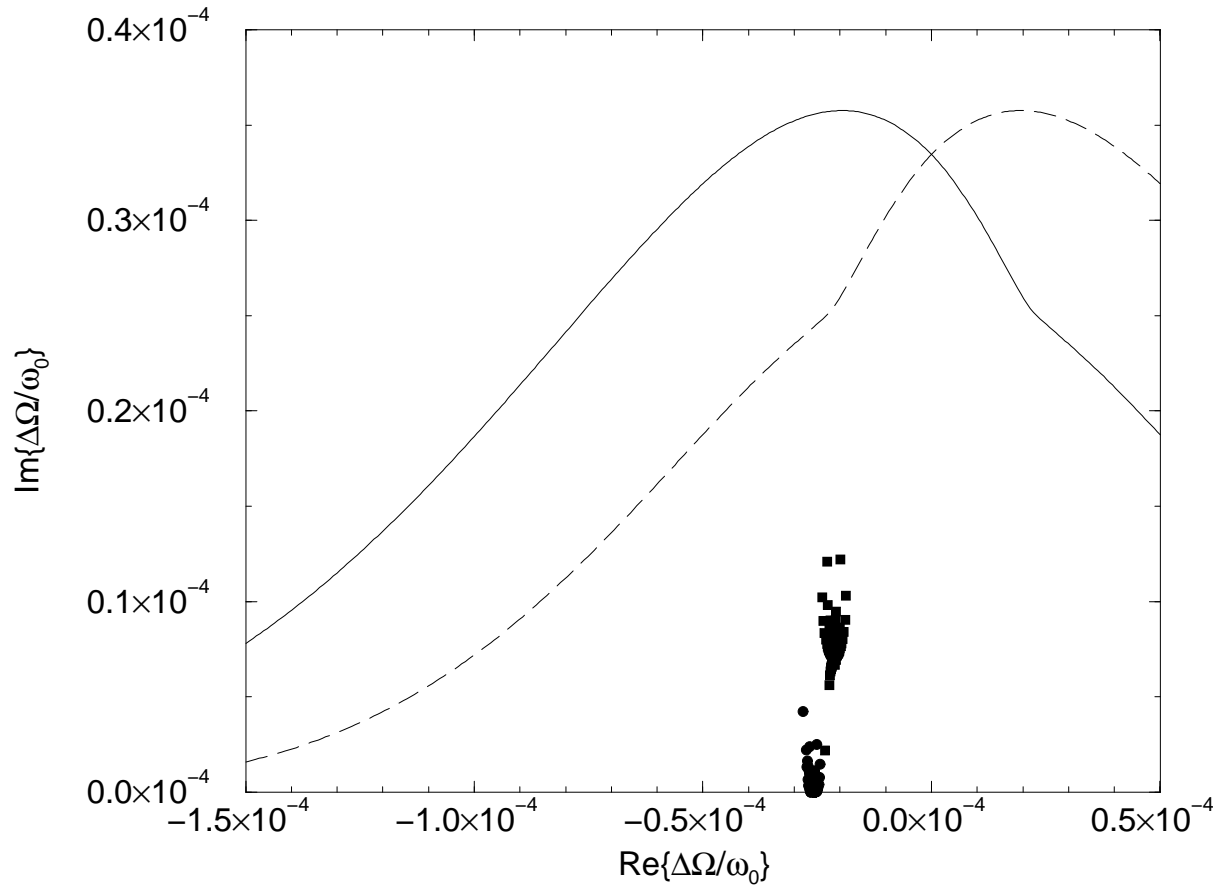


Figure 5: Complex coherent frequencies of $m = 0$ modes for multiple symmetric bunches at top energy with 16% of the nominal current, compared to Landau damping threshold curves. The \bullet are for a chromaticity of 0, and the \blacksquare are for a chromaticity of -15 . The Landau damping curves assume that $a_{xx} = \pm 3.2 \times 10^{-5}$ (see the text), and that the beam is always collimated at 6σ (and no less). The solid line is for a_{xx} negative, and the dashed line is for a_{xx} positive. Note that the range of $\Delta\Omega$ in this figure is different than that of previous figures.

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